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STRESS DETERMINATION WITH UNDERCORING AND PRESSURE COMPENSATION

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STRESS DETERMINATION WITH UNDERCORING AND PRESSURE COMPENSATION

by

G. Herget* and F. Kapeller**

SUMMARY

Ground stress determinations with compensation methods (flatjack) are restricted to locations close to the excavation surface. In the following report, an experiment is described which could lead to development of a compensation measurement method for in situ stress determination deep in a drill hole.

The concept is to drill from the bottom of a six inch hole two parallel 1-1/2 in. drillholes and install USBM meters in them. This would be followed by drilling between the instrumented holes a 1-7/8 in. hole, resulting in strain relief recorded by the USBM meters. Following this, a flatjack would be installed in the 1-7/8 in. hole to compensate for the observed strain relief. The pressure recorded at compensation would be an indication of the stress acting at right angles to the flatjack orientation.

To prove the principle, measurements were carried out in plaster cylinders with 20 cm diameter and 40 cm height. Flatjacks were developed for this purpose. During calibration of the USBM meters it was found that total travel of cantilevers is limited to 0.023" (4600 $\mu\epsilon$) per cantilever. Contact buttons need to be set close to hole tolerances and need to be shimmed carefully so that opposite measuring buttons are equidistant from the centre line.

The experiment proved the principle but the flatjack compensation was disappointing, because of the strong curvature observed in the relationship of flatjack pressure and axial strain at low uniaxial stresses (2.34 MPa, 340 psi). Thus at the point of compensation, the flatjack pressures were higher than the axial stresses on the sample.

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This effect is probably due to the unfavourable width/thickness ratio for the narrow flatjacks. The effect can be accounted for by calibration and will be less significant as the procedure is applied at higher stresses.

The studied method has similar limitations as any overcoring method, in that the material has to stay in the elastic range during the total procedure required for drilling and pressure application.

DÉTERMINATION DES CONTRAINTES PAR LE SOUS-CARROTAGE
ET LA COMPENSATION EN PRESSION

par

G. Herget* et F. Kapeller**

SOMMAIRE

Les mesures de la contrainte du sol à l'aide des méthodes de compensation (vérins plats) sont limitées aux endroits situés près de la surface d'excavation. On fait dans le présent rapport une description d'un essai qui pourrait mener à la mise au point d'une méthode pour mesurer la compensation lors de la détermination in situ des contraintes dans un trou de forage profond.

Le concept est de forer au fond d'un trou de forage mesurant six pouces, deux trous de sonde parallèles de 1 pouce 1/2 et d'y installer des compteurs USBM. Ensuite, on fore un trou de 1 pouce 7/8 entre les deux trous munis des compteurs, entraînant une réduction de tension enregistrée par les compteurs USBM. On installe, après cela, un vérin plat dans le trou de 1 pouce 7/8 dans le but de compenser la réduction de tension observée. La pression enregistrée au moment de la compensation serait une indication de la contrainte qui s'exerce à angle droit avec l'orientation du vérin plat.

Afin d'établir le principe, des mesures ont été prises dans des cylindres en plâtre mesurant 20 cm de diamètre et 40 cm de hauteur. Des vérins plats ont été mis au point pour ce faire. Au cours de l'étalonnage des compteurs USBM, on a trouvé que le déplacement total des poutres en porte-à-faux était de 0,023 pouce (4 600 μ c) par poutre. Les gouttes-de-sulf

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doivent être placées près des limites du trou et calées avec soins, afin que les boutons de mesure opposés soient équidistants de la ligne centrale.

L'essai a prouvé le principe, mais la compensation par le vérin plat était décevante en raison de la forte courbature observée dans le rapport entre la pression du vérin plat et la tension axiale lors de contraintes uniaxiales faibles (2,34 MPa, 340 psi). Par conséquent, les pressions du vérin plat au point de compensation étaient plus élevées que les contraintes axiales exercées sur l'échantillon.

Cet effet est probablement causé par un rapport largeur/épaisseur défavorable pour les vérins plats étroits. L'effet peut être justifié par étalonnage et sera moins important à mesure que la méthode sera appliquée à des contraintes plus élevées.

La méthode étudiée a des restrictions semblables à celles de n'importe laquelle méthode de surcarottage, en ce sens que le matériau doit demeurer dans la phase élastique durant tout le procédé nécessaire de forage et d'application de la pression.

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1. INTRODUCTION

Stress determinations with the principle of undercoring have been carried out by the United States Bureau of Mines in 1982 on the surface of excavation walls by mounting measuring pins in a 25 cm (10 in.) circle. A six inch hole is drilled in the centre of the ring and from ring convergence, stresses can be calculated. The distance between pins is measured by a Whittemore-type mechanical strain gauge (1). Elastic modulus and Poisson's ratio are determined on the sample recovered from drilling the central hole.

Undercoring offers the potential of determination of in situ stresses and deformation moduli in one location. The undercoring approach described in reference 1 is strictly a surface technique and carries with it the problems of near surface cracks from blast damage and stress concentrations due to the geometry of excavation surfaces. Installation of measuring pins is cumbersome. However, to explore the potential of undercoring by measuring strain recovery with strain gauged cantilevers, a number of tests were carried out on 20 cm diameter plaster cylinders.

2. EXPERIMENTAL LAYOUT

The concept was to prepare plaster specimen with a diameter of 20 cm and a height of 40 cm and to install two USBM deformation meters at equal distance from mid height of the sample. Then with the plaster cylinder under load, an undercoring hole would be drilled at exactly mid height (Fig. 1). During drilling of the central hole, axial strain relief would be recorded by the USBM meters.

Following this, a flatjack would be installed at right angles to the axial load in the undercoring hole with the aim that during pressurization of the flatjack, compensation of earlier strain relief would occur at the point when the flatjack pressure reaches the pressure applied to the sample in axial direction.

2.1 PHYSICAL PROPERTIES OF PLASTER

Plaster has been very well researched as a model material and it is sufficient to quote some of the more pertinent properties as given in references 2 and 3. The plaster/water ratio determines practically the resulting physical properties and characteristic data are given in Fig. 2.

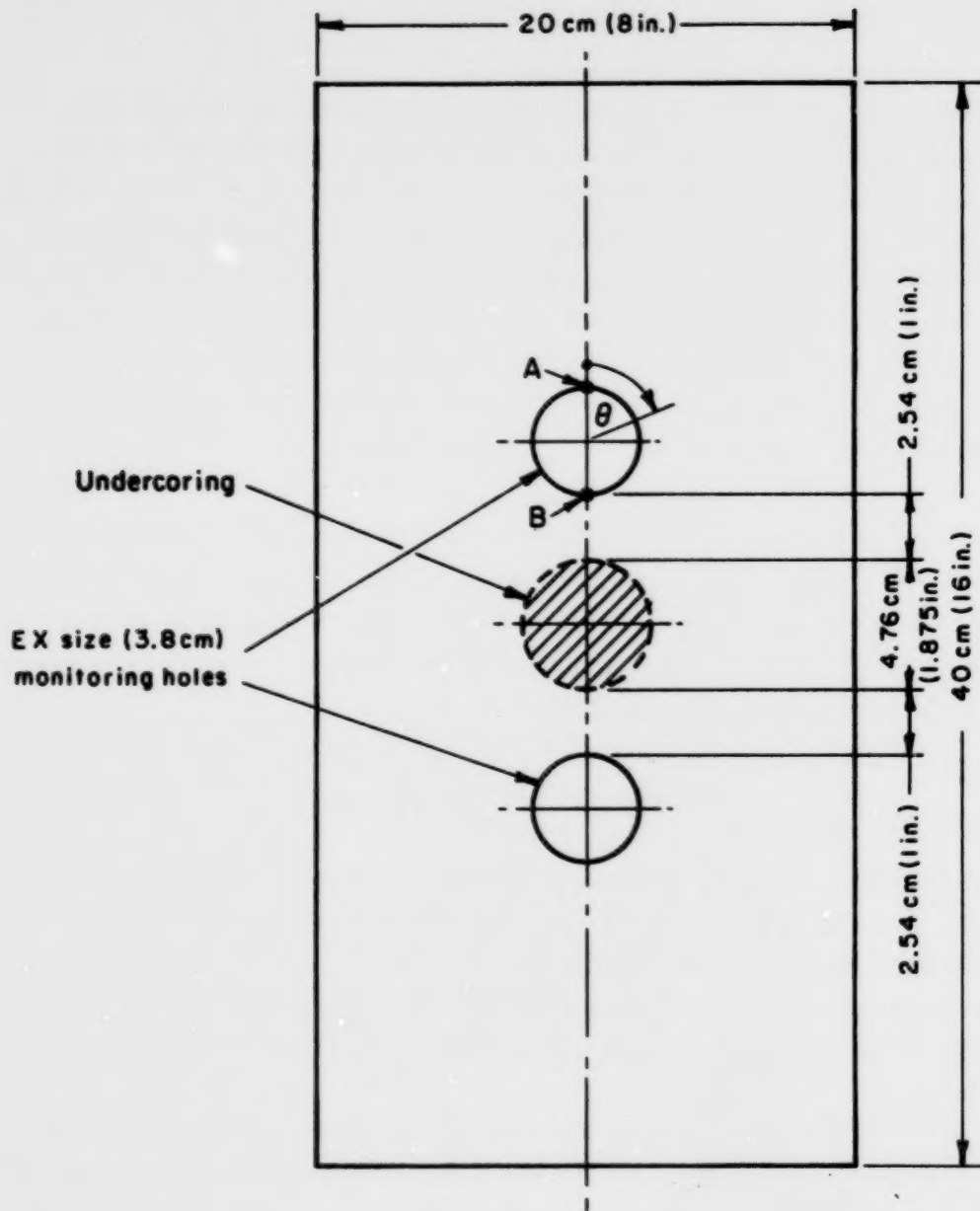


Fig. 1 - Drill hole layout for 20 cm diameter plaster cylinder

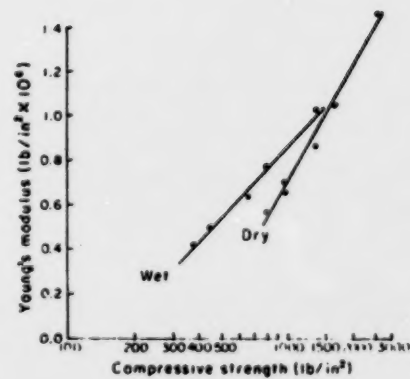
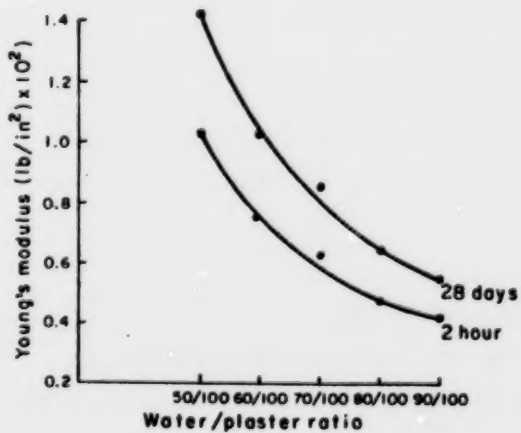
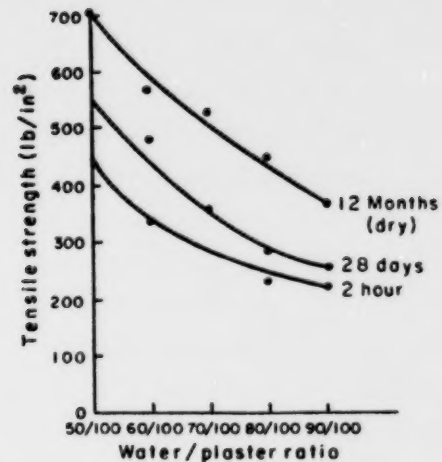
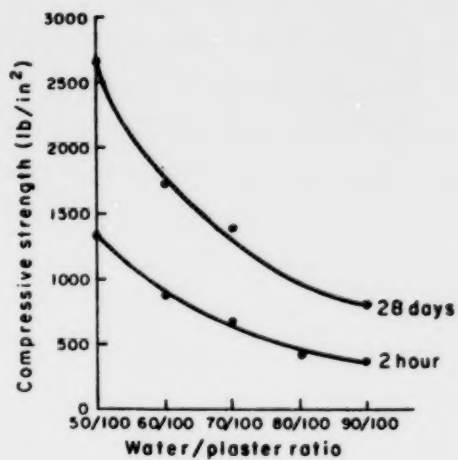


Fig. 2 - Variation of plaster strength with water/plaster ratio (2)

Four plaster specimens were mixed in a water/plaster ratio of 1:2 and poured into cardboard tubes 20.3 cm (8 in.) diameter and 43.2 cm (17 in.) high. The plaster/water mix was stirred gently to reduce content of air bubbles and ensure a homogenous mix.

After curing for ten days, the cardboard tubes were removed to allow drying and one week later, the sample ends were ground parallel. The samples were measured in regard to height and diameter. Strain gauges (SR4-FAE-50-12-S6-120 Ω) were glued in pairs at mid height in vertical and horizontal direction. 105 days after pouring sample No. 1, it was loaded in a frame to 10.3 MPa (1500 psi) to determine the elastic modulus and Poisson's ratio. This stress level was close to the breaking strength of the material and load cycles for other plaster samples were kept to below 4 MPa (600 psi). Poissons ratios amounted to 0.226 ± 0.028 and elastic moduli to (2.5 ± 0.6) MPa [$(1.38 \pm 0.08)10^6$ psi] (Table 1).

After testing of the large samples, smaller samples were drilled out from undamaged parts. Loading of 4.8 cm (1.89 in.) diameter samples with a height to width ratio of 2:1 resulted in a uniaxial compressive strength of $17.95 \text{ MPa} \pm 0.90 \text{ MPa}$ (2603 ± 130 psi). Brazilian discs of 4.8 to 20.3 cm diam (1.9 to 8 in.) yielded a tensile strength of about 1.8 to 3.0 MPa (261-435 psi). Results are comparable to earlier work on plaster as shown in Fig. 2.

Samples derived from the large cylinder after load cycling showed in general more ductility. This indicates microfracture development during repeated loading. Values in Table 2 should therefore be regarded as minimum values.

2.2 MONITORING OF PLASTER DEFORMATION WITH USBM METERS

A hydraulic loading frame with a capacity of 50 t was mounted on a milling machine to allow drilling of holes at right angles to the axis of the plaster sample while under load (Fig. 3).

Two holes of 3.81 cm (1.5 in.) diameter were drilled at a distance of 6.82 cm (2.687 in.) from mid height of the plaster samples. The holes were drilled dry and the drilling was done with slow advance to avoid the sample from heating up. The obtained drill holes were smooth but relatively soft. A thin coat of spray paint was applied to reduce gouging of the drill hole wall by the buttons of the USBM deformation meter during installation. Calibration of USBM meters 434 and 435 are given in Appendix A (4).

Table 1 - Physical Properties of plaster after 125 days

Spec. No.	Load range (MPa)	Diameter (cm)	Length (cm)	E (GPa)	ν	Density (kg/m ³)	Remarks
1	0-10.34	20.269	41.33	8.83 ¹⁾	0.207	1,337	1) secant modulus
1	10.34-0	20.269	41.33	9.38	0.212		
2	0-2.34	20.295	40.33	8.69	0.221	1,337	1 MPa = 145.04 psi
2	2.34-0	20.295	40.33	8.89	0.223		1 kg/m ³ = 0.0624 lb/ft ³
3	0-2.34	20.295	40.33	10.20	0.201	1,325	
3	2.34-0	20.295	40.33	10.20	0.197		
4	0-2.34(4 cycles)	20.269	41.33	9.95 ± 0.04 ¹⁾	0.275 ± 0.033	1,325	
4	2.34-0(3 cycles)	20.269	41.33	9.89 ± 0.06 ¹⁾	0.263 ± 0.021		
				9.50 ± 0.6	0.226 ± 0.023	1346.0 ± 26.7	

Table 2 - Physical properties of plaster cylinders obtained from large samples after load cycling

Compression Testing: 4.814 cm diam cylinders					
Specimen	Length	Qo	E	v	Remarks
No.	(cm)	(MPa)	(GPa)		
3-1	9.960	17.91	7.49 ¹⁾	0.29	1) Tangent modulus
3-2	10.100	18.79	4.86	0.22	
3-3	9.970	18.68	6.37	-	1 MPa - 145 psi
3-4	10.060	17.58	6.79	-	1kg/m ³ =0.0624 lb/ft ³
3-5	9.982	16.59	5.49	-	
3-6	9.958	18.24	6.87	-	
3-7	10.040	16.48	5.83	-	
3-8	10.050	18.46	6.58	0.30	
3-9	10.020	18.79	6.04	-	
		<u>17.95 ± 0.90</u>	<u>6.25 ± 0.80</u>	<u>0.27 ± 0.04</u>	

Brazilian disc test: 4.814 cm diam

Specimen	Thickness	Tensile strength
No.	(cm)	(MPa)
1-1	2.590	1.593
1-2	2.540	2.832
1-3	2.422	3.200
1-4	2.630	2.886
1-5	2.620	2.594
1-6	2.570	2.850
		<u>2.659 ± 0.557</u>

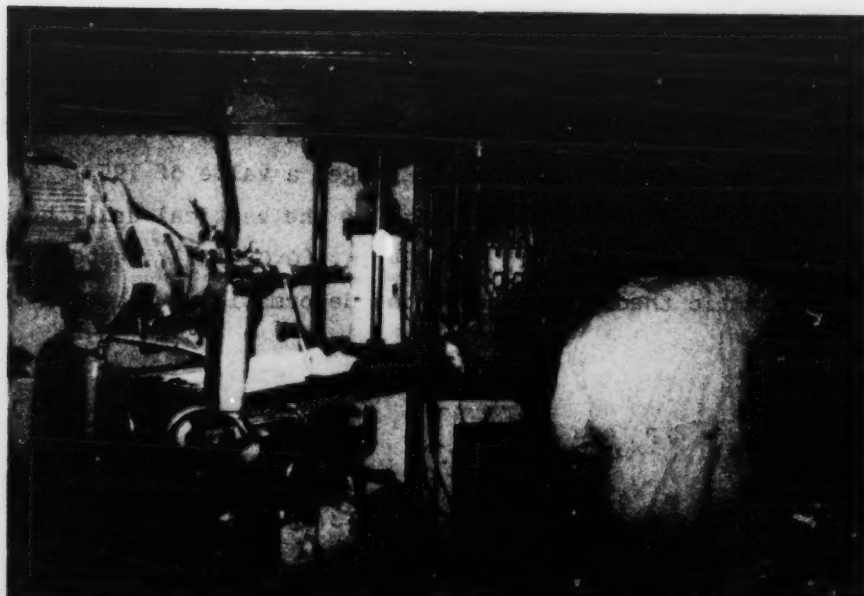
Brazilian disc test: 6.348 cm diam

2-1	3.412	2.880
2-2	3.344	3.005
2-3	3.388	3.629
2-4	3.430	3.018
2-5	3.368	3.465
2-6	3.360	2.430
		<u>3.071 ± 0.429</u>

Brazilian disc test: 20.31 cm diam

4-1	3.850	0.537 ²⁾	2) sample showed hairline crack before testing, excluded from average
4-2	3.675	1.702	
4-3	3.800	2.109	
4-4	3.925	1.664	
		<u>1.825 ± 0.247</u>	

(a)



(b)

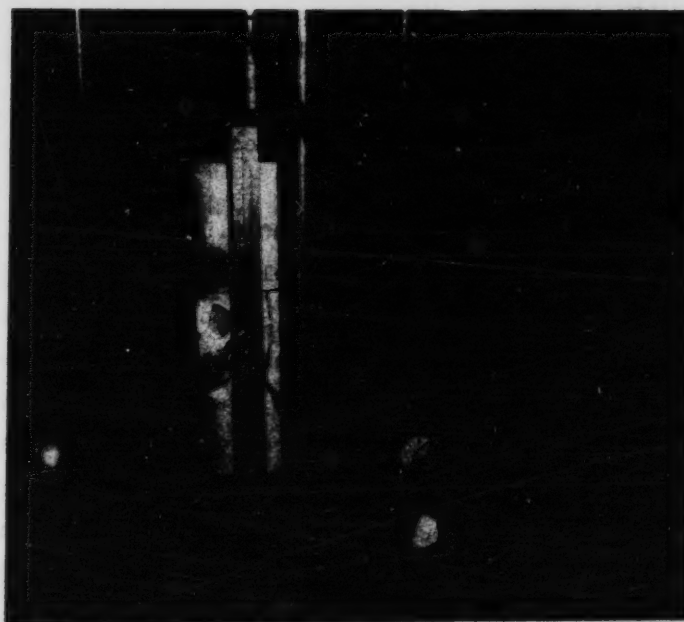


Fig. 3 - Hole drilling and loading arrangement
for 20 cm diameter plaster samples

(a) drilling setup;

(b) USBM meter and undercoring hole

A sketch of the Ex hole arrangement is given in Fig. 1. After installation of the USBM meters, the plaster cylinders were loaded to 2.34 MPa (340 psi) and on average the upper hole (434 gauge) registered a vertical strain of 206 $\mu\epsilon$ and the lower hole (435 gauge) a value of 194 $\mu\epsilon$ as shown in Table 3. This amounts to a deformation of the vertical drill hole diameter by 0.00105 in. (0.027 mm) and 0.00094 in. (0.024 mm), respectively.

From elastic theory (5) the radial deformation (r) across the diameter $r = 1.5$ in.:

$$U = r (p_x + 2 p_x \cos 2\theta) / E$$

with $\theta = 0$, $p_x = 340$ psi, $r = 1.5$ in., $E = 1.377 \times 10^6$ psi,

$$U = 0.001111 \text{ in. (0.028 mm)}$$

which provides close agreement.

2.3 UNDERCORING WITH A CENTRAL HOLE

After it had been established that both USBM meters yielded reproducible data during loading and unloading of the plaster samples, the objective was to drill a central hole between the Ex holes while the specimen was under load and measure the strain relief (Fig. 1).

A coarse tungsten carbide bit with an O.D. of 4.76 cm (1.875 in.) was used to drill the hole dry with a dust collector and an advance of 1.3 cm min (0.5 in./min). The sample was loaded to 340 psi. Strain relief was indicated early but was less than expected because the plaster specimen was heating up to about 45-55°C during drilling. Full strain recovery was only observed after 30 min when cooling with compressed air to laboratory temperature. The average strain relief for the monitoring holes was $63 \mu\epsilon \pm 13.6 \mu\epsilon$ with the upper hole recovering 69 $\mu\epsilon$ and the lower hole recording 57 $\mu\epsilon$ in vertical direction (V) as shown in Fig. 4.

To obtain a comparison to the observed strain relief, the difference was calculated for the axial deformation recorded by the USBM meters in the three-hole and two-hole configuration, when the plaster samples were loaded from 0 to 340 psi (Table 3). Again the upper hole generally recorded slightly higher strain differences, e.g., 53 $\mu\epsilon$ compared to the lower hole with 38 $\mu\epsilon$.

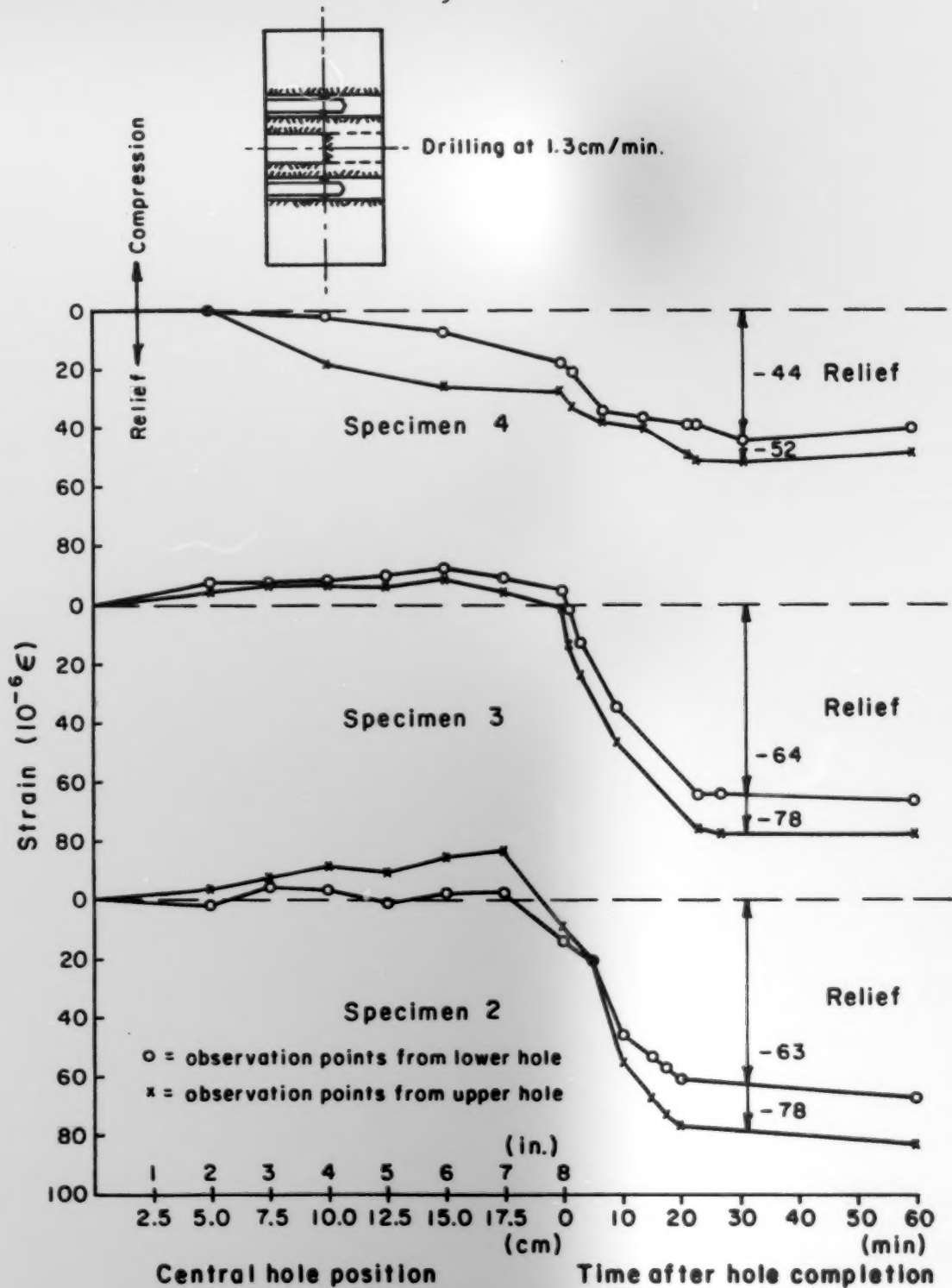


Fig. 4 - Strain recovery during undercoring with axial pressure at 340 psi

Table 3 - Strain (10^{-6}) recorded by two USBM meters in 20 cm diam plaster cylinders subjected to a pressure of 2.34 MPa (340 psi)

Specimen No.	Range (MPa)	Cycles	V	Upper hole		V	Lower hole	
				60°L	60°R		60°L	60°R
Loading of plaster cylinder with monitoring holes only								
2		3	201 ± 2	12 ± 0	4 ± 0	220 ± 5	-5 ± 3	-2 ± 1
3		3	213 ± 3	2 ± 1	-10 ± 1	181 ± 1	14 ± 0	-6 ± 1
4		5	204 ± 2	3 ± 1	-22 ± 3	182 ± 3	18 ± 5	-10 ± 1
Loading of plaster cylinder with monitoring holes and under coring hole								
2		2	127 ± 20	26 ± 13	22 ± 18	170 ± 13	22 ± 8	-12 ± 4
3		5	169 ± 6	11 ± 5	-16 ± 11	137 ± 4	13 ± 8	-3 ± 5
4		10	163 ± 3	20 ± 6	23 ± 2	161 ± 5	27 ± 2	19 ± 16
Strain difference in vertical direction (V) calculated from USBM deformation meter readings								
2			74	-	-	50	-	-
3			44	-	-	44	-	-
4			41	-	-	21	-	-
			53 ± 18.2			38.3 ± 15.3		

2.4 FLATJACK COMPENSATION

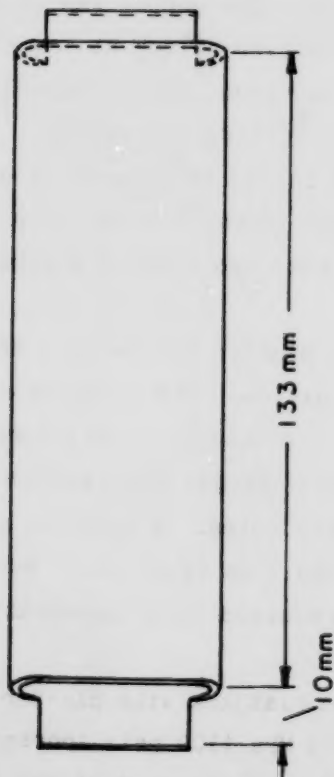
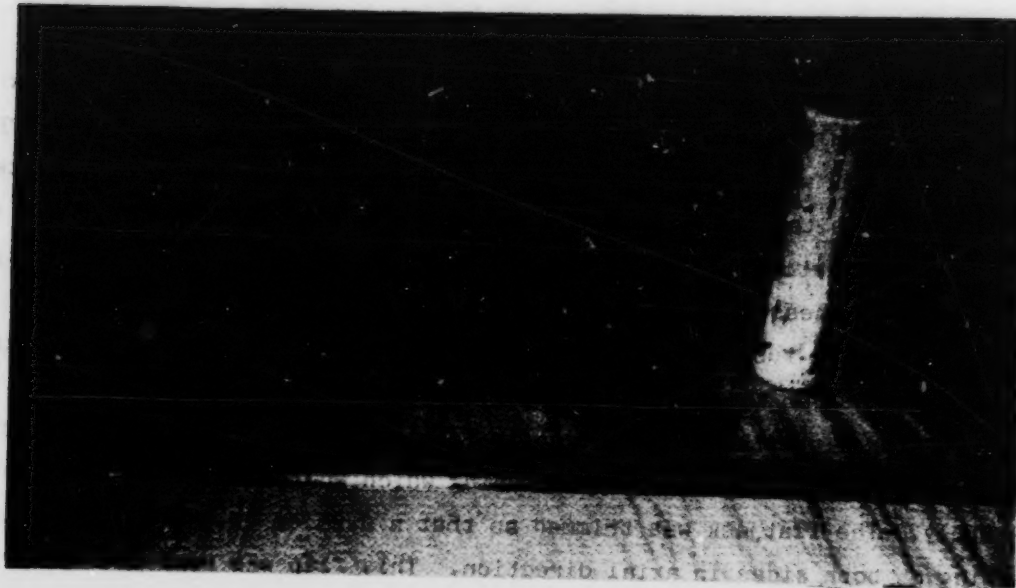
During drilling of the central hole, stress relief occurred in axial direction between the two Ex holes. To compensate for this strain recovery, a copper flatjack was developed with a capacity of 20 MPa (3000 psi). After a few trials a suitable flatjack with a size of 133 mm by 31 mm (5.23 in. x 1.2 in.), was relatively easily built from 3/4 in. copper tubing (water pipe) with a wall thickness of about 1 mm (0.04 in.).

First the tubing was annealed by heating to 400-500°C and quenching in cold water. Then the pipe was bent into an oval shape, and two 1/8 in. steel rods were inserted at the edges to form the flat of the flatjack and to provide space for the 1/8 in. copper tubing which would be hooked up to the oil supply. The flatjack was trimmed so that a 0.95 cm (0.357 in.) flap was extending on both sides in axial direction. This flap was bent over to provide for a stronger soldering joint (Fig. 5). The copper was thoroughly cleaned and the flatjack was soldered with silver solder at the edges and very generously at the copper tubes. One pipe was bent over (crimped) after filling with oil and to the other a swadge lock fitting was added.

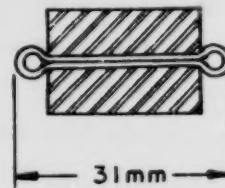
After cooling, the flatjacks were tested in a large vice between steel platen for leaks. To fit the flatjack in the central hole of the large plaster cylinder, the flatjack was fitted with two plaster halves to reach a diameter of 46 mm (1.8 in.).

Installation of the flatjack with plaster halves into the central hole of the specimen presented some difficulties. The plaster/specimen contact was uneven and due to point loading, resulted in a very irregular stress distribution. Casting the flatjack in place changed the experimental set up by increasing the wall thickness between the holes. A solution was found by placing a rubber strip 5 cm (2 in.) wide and 1 mm (0.04 in.) thick above and below the plaster halves (Fig. 5). This resulted in an acceptable stress distribution.

Following the installation of the flatjack with plaster halves, the pressure in the flatjack was raised in 0.69 MPa (100 psi) increments with the 20 cm (8 in.) diam plaster cylinder loaded to at least 2.34 MPa (340 psi). Pressure increase of the flatjack was stopped when the USBM meters showed that the pressure compensated the strain relief observed during drilling of the central hole.

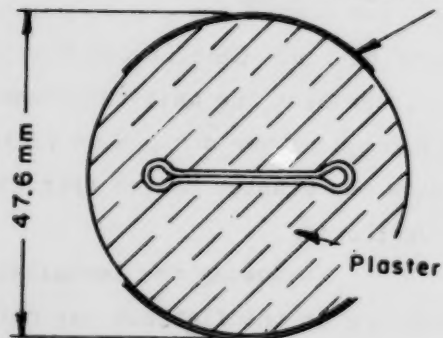


A: Shape of flattened pipe before soldering



B: Steel blocks to contour flatjack and for leak testing

Optional thin rubber shim
for even load distribution



C: Flatjack embedded in plaster

Fig. 5 - Preparation of flatjack system

Figure 6 shows flatjack pressure versus axial strain recorded by the USBM deformation meters. The compensation characteristic is very curved, showing a relatively stiff behaviour at low flatjack pressures and a considerably softer behaviour at higher stresses. This non-linearity was confirmed by all the compensation tests performed on samples 2, 3 and 4.

The reason for the pronounced curvature is not fully understood. It might well be that the flatjack loading system is very stiff at low pressures compared to the strength of the plaster and that this affect will diminish at higher pressures.

The other cause is probably due to the stress distribution around the flatjack. The flatjack has a thickness of 5.2 mm (0.2 in.) at the edges and a width of 31 mm (1.2 in.). This unfavourable width to thickness ratio will not only transmit pressure in axial direction but will also develop a pressure component in horizontal direction. Such a component will reduce axial strain in a uniaxial loading condition.

This characteristic would be eliminated by using calibration curves for analysis, and would be less pronounced if measurements are made in a stress field approaching hydrostatic conditions.

To prove both points more experimental effort is required. A repeat of the above experiment with square blocks of fine grained rock or metal would be useful.

3. CONCLUSIONS

1. Undercoring of a 20 cm (8 in.) diameter plaster cylinder under load allowed measurements of strain recovery in axial direction.
2. Compensation of the effect of undercoring by flatjacks showed that the relationship of flatjack pressure to axial strain is strongly curved. This curvature is probably the result of flatjack geometry and relative stiffness of plaster sample and flatjack assembly.
3. The procedure of stress determination by undercoring and flatjack compensation would be most suited in stress fields which are close to hydrostatic.
4. The above procedure for ground stress determination has similar limitations as any overcoring procedure. The procedure of undercoring and flatjack compensation requires that the material involved, stays in the elastic range.

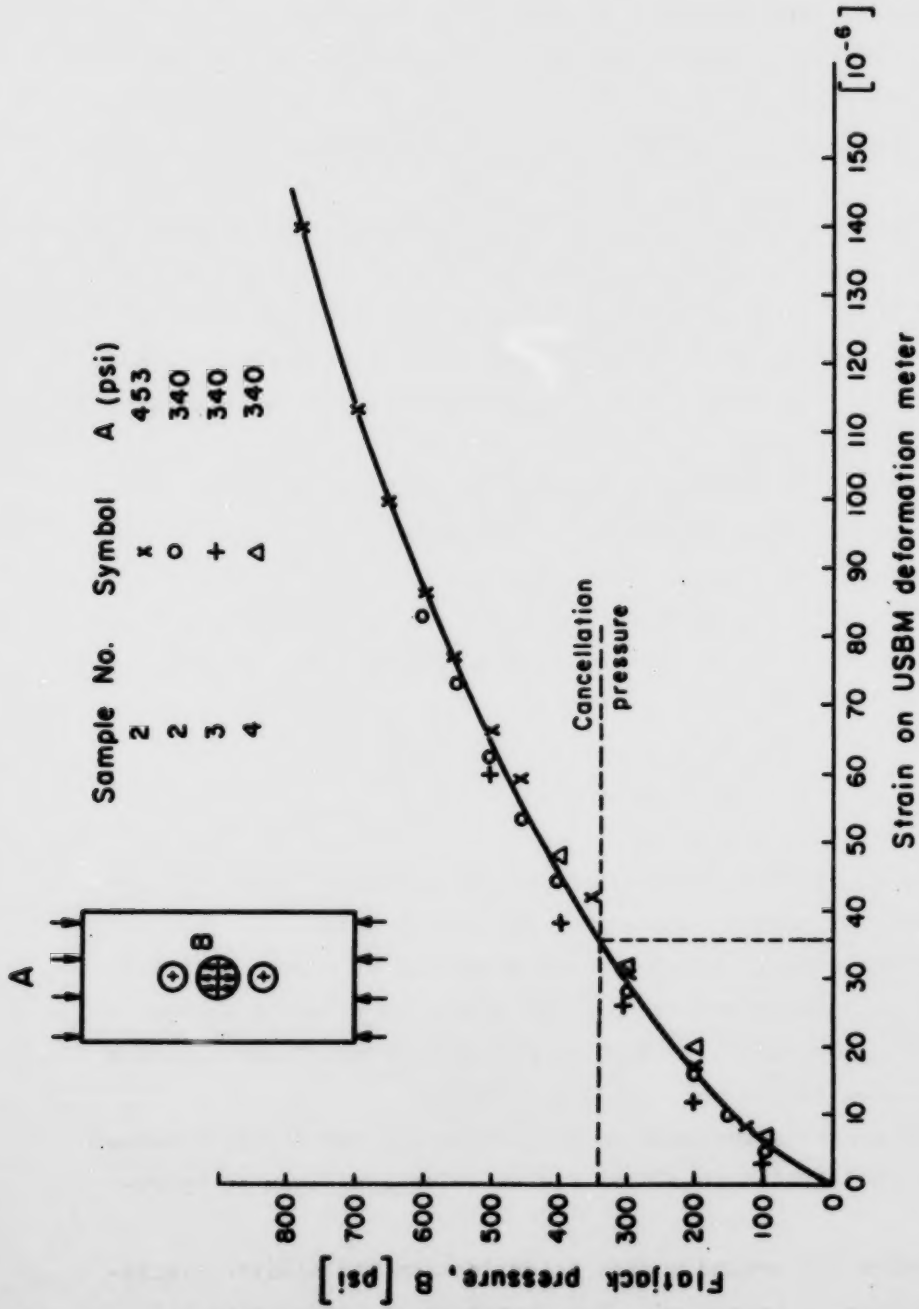


Fig. 6 - Compensation of strain recovery by flatjack pressurization

4. ACKNOWLEDGEMENT

The author appreciates the effort by B. Gorski in preparing and testing plaster samples in regard to uniaxial compressive strength, elastic modulus and Poisson's ratio. J. Folta and D. Dugmore prepared the line drawings.

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APPENDIX A - CALIBRATION OF USBM

DEFORMATION METERS

Two USBM meters (No. 434 and No. 435) were obtained from Rogers Arms and Machine Co. Inc., Grand Junction, Colorado in 1978. For this study calibrations were carried out for each unit in a special jig with two micrometers by compressing each button simultaneously by 0.5/1000 in. Repeated calibration under laboratory conditions showed that the units are stable and both produce similar results. The mean calibration values are given below in 10^{-6} in. per microstrain. L (left) and R (right) are identified by an observer looking at the backend of the deformation meter.

Tool No.	V	60°L	60°R
434	5.071	5.000	4.900
435	4.846	4.667	4.929

Calibration curves are reproduced in Fig. A-1 to A-6 for each diameter. The maximum deflection per transducer is 0.023 in (0.58 mm), which results in a strain change of 4600×10^{-6} in/in. in compression. This limit occurs due to a safety stop (block) as described by Hooker (1974). Any additional deformation will not be recorded. It also was noticed that readings will be the most precise, if buttons are equidistant from the central instrument axis. Therefore, any adjustment of button length with the supplied washers has to be done with great care.

Calibrations were carried out before and after the tests and showed that the units are stable.

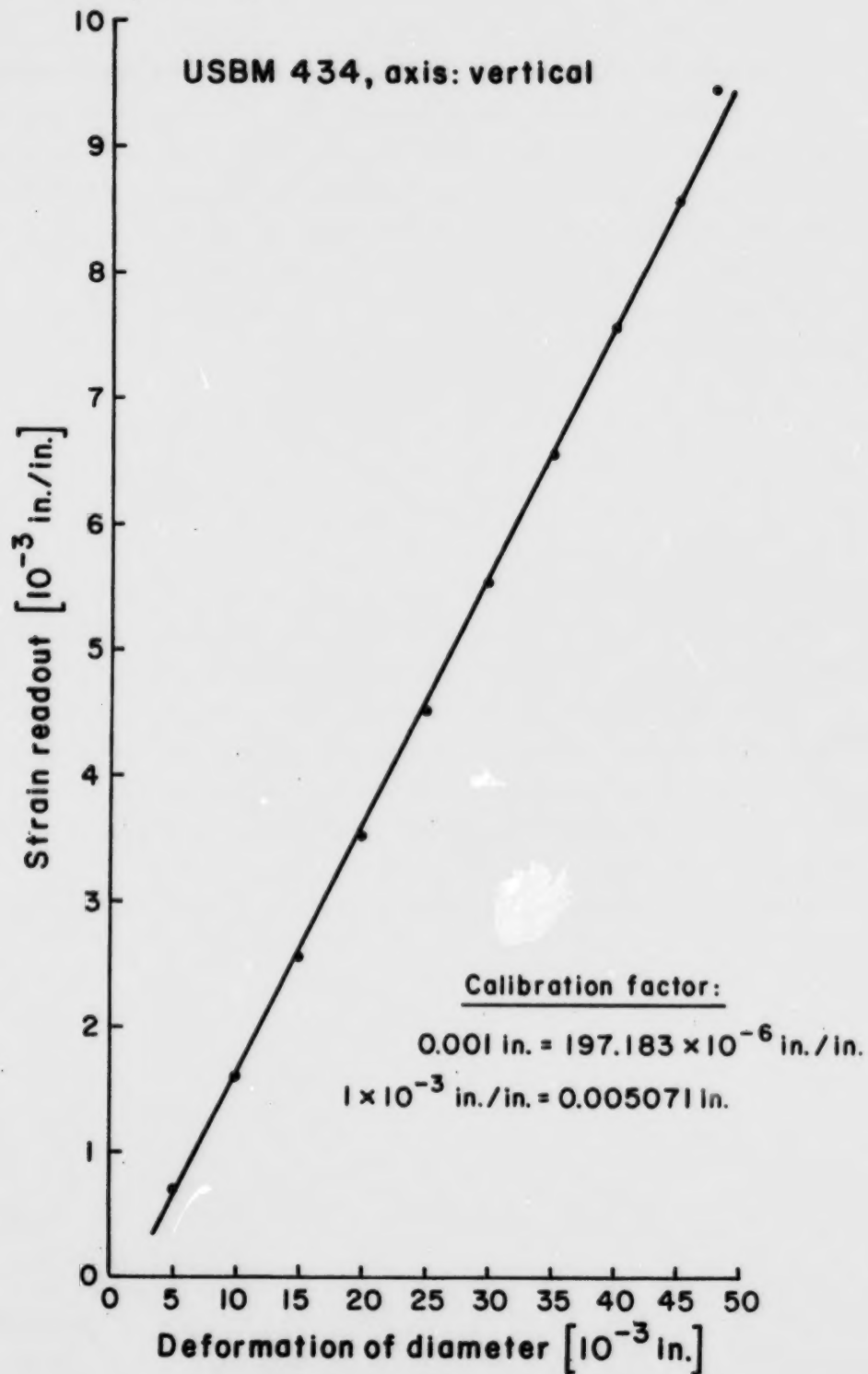


Fig. A-1 - Calibration of USBM 434, vertical axis

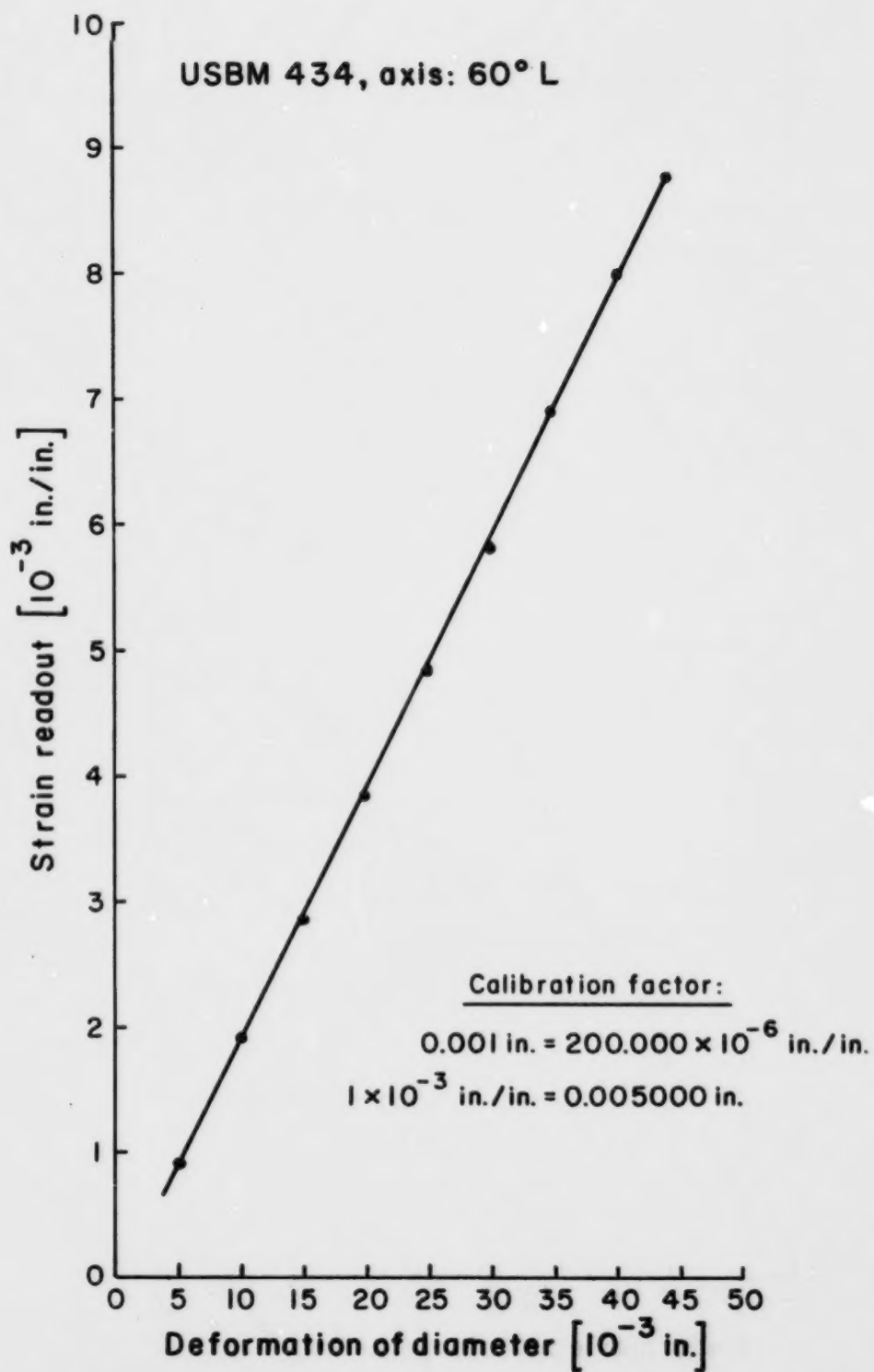


Fig. A-2 - Calibration of USBM 434, left axis

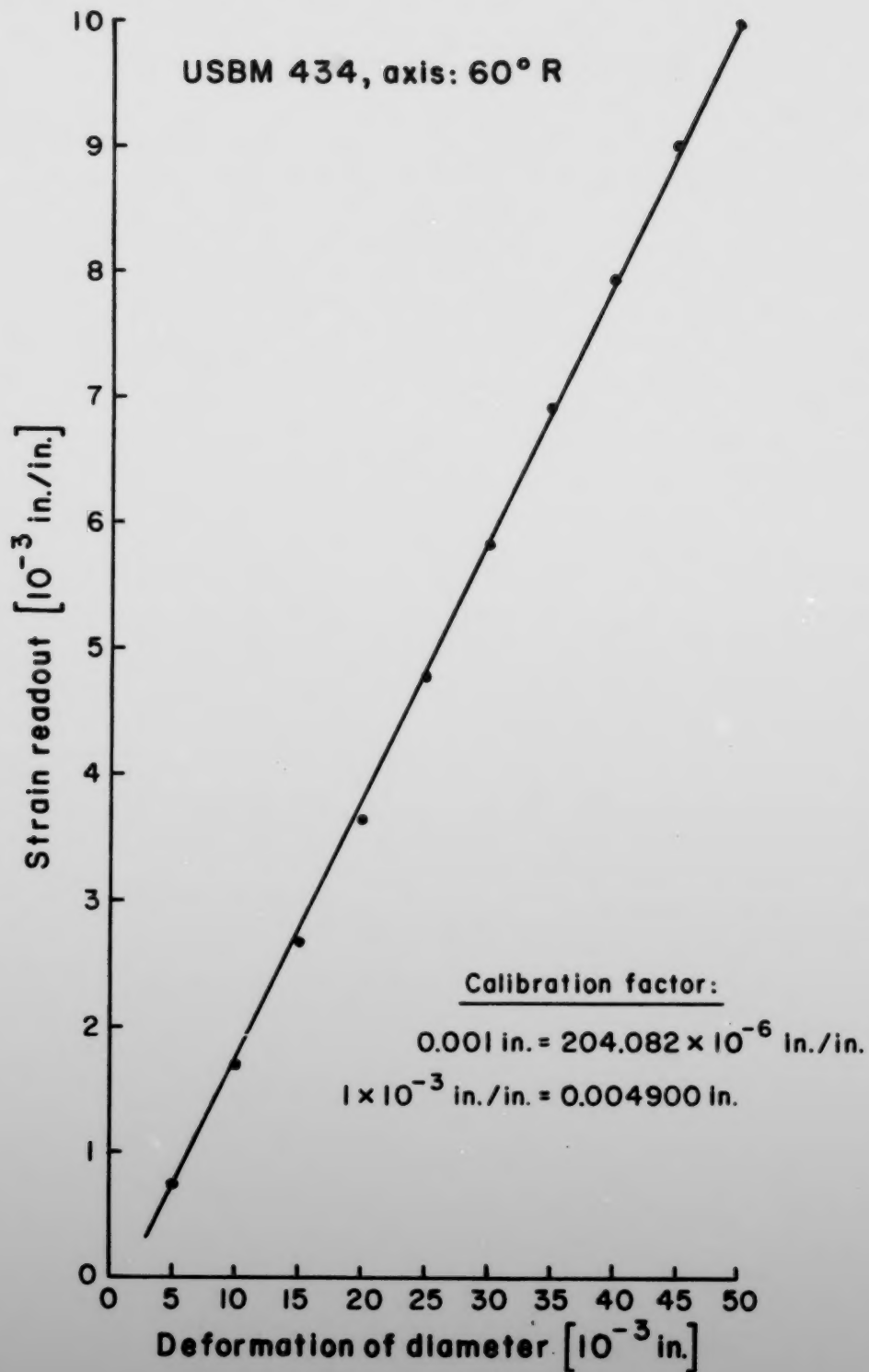


Fig. A-3 - Calibration of USBM 434, right axis

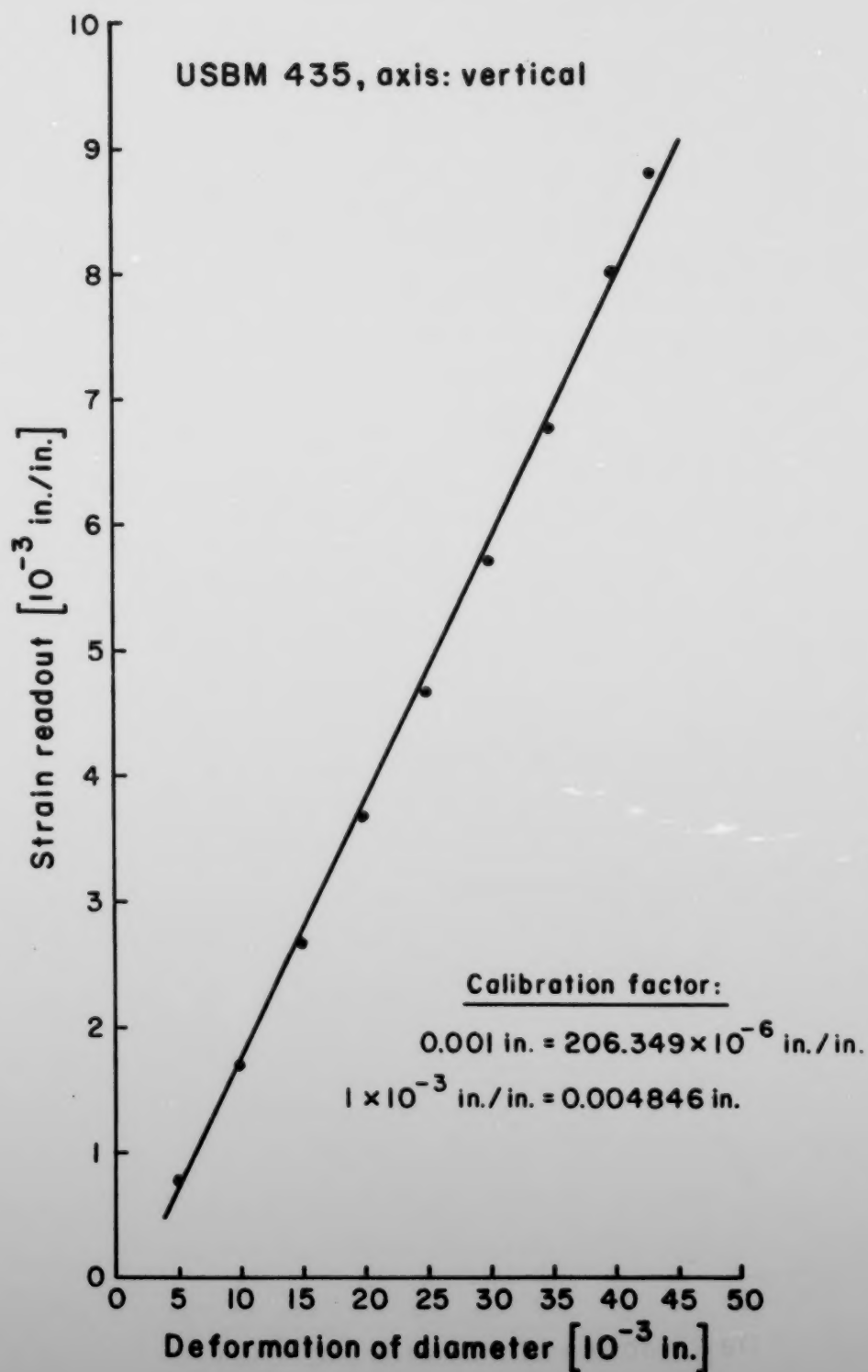


Fig. A-4 - Calibration of USBM 435, vertical axis

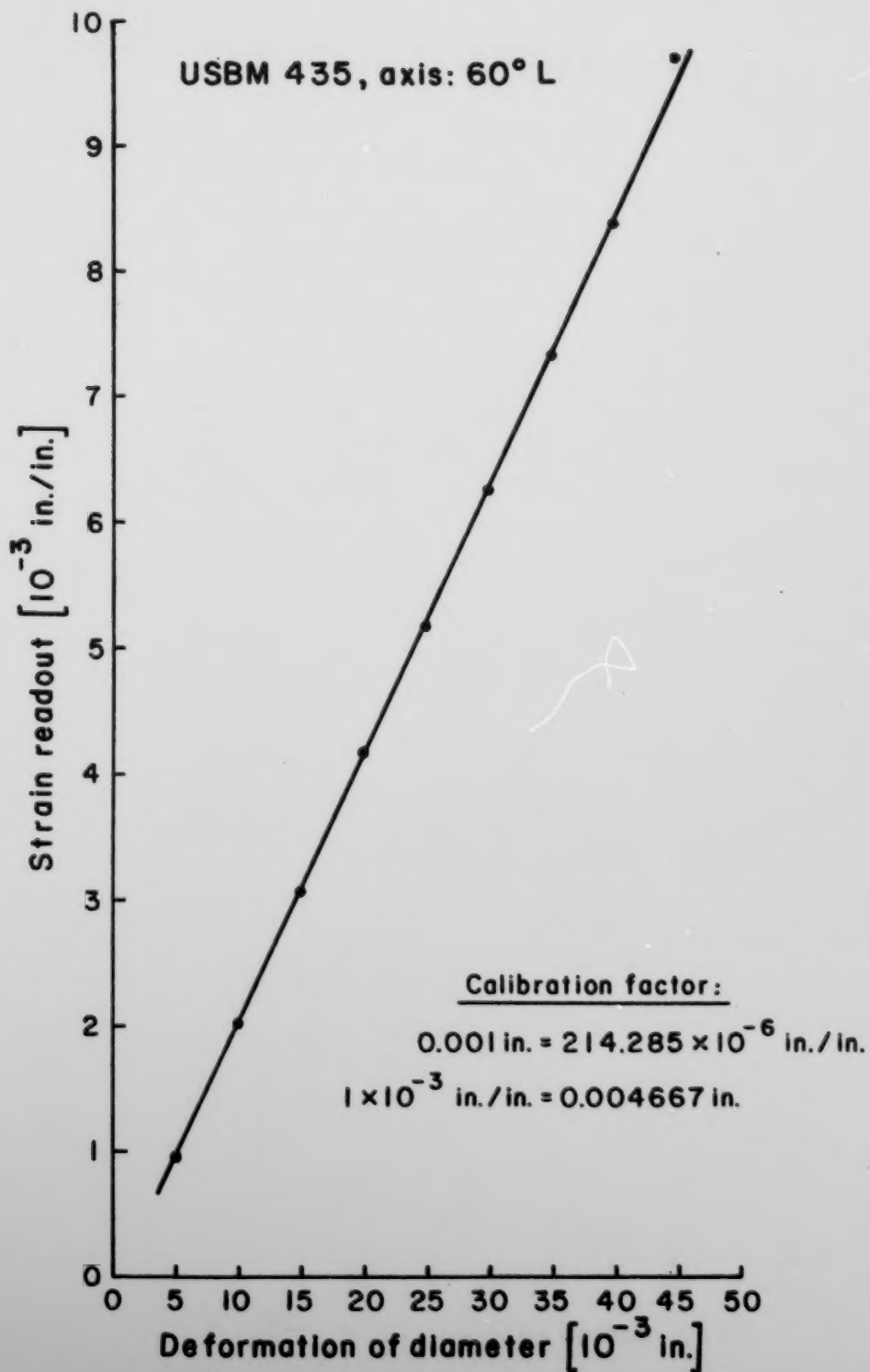


Fig. A-5 - Calibration of USBM 435, left axis

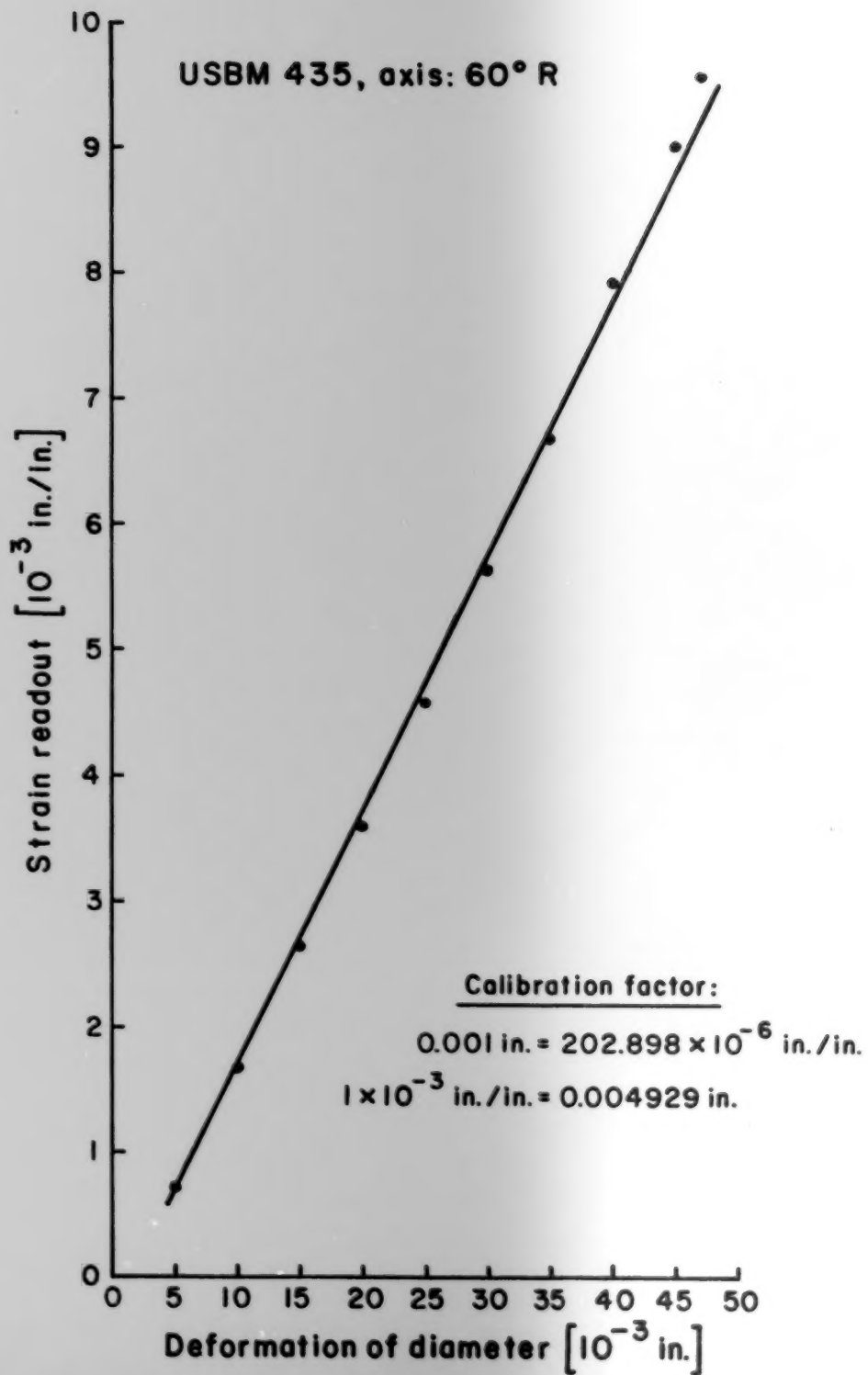


Fig. A-6 - Calibration of USBM 435, right axis